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Is the perception of brightness different in poor readers? ☆

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Abstract

The transient system deficit hypothesis (TSDH) of specific reading disability [Percept. Psychophys. 40 (1986) 440] remains contentious. As part of a study examining multiple measures of transient and sustained system function, heterochromatic flicker matching (HFM) and brightness matching (HBM) were assessed in 30 poor readers (9.11 ± 0.68 years) and 30 age, grade and sex matched controls (9.24 ± 0.73 years). HBM and HFM are known to reflect the processing of brightness and luminance information and have been related to the function of magnocellular and parvocellular visual sub-systems. Flicker and brightness matches were determined for blue, green, yellow and red stimuli on Macintosh colour displays using 2AFC and double interleaved random staircases. A ratio of the luminances for brightness and flicker matches represented performance. A significant difference between controls and poor readers in performance for red and blue stimuli was found indicating different visual function in poor readers. While not providing direct support for the transient system deficit hypothesis, this effect implies a mismatch between those achromatic systems that subserve HFM and those more complex mechanisms involved in HBM. The most important aspect of this finding is that poor readers and normal controls could be differentiated on the basis of a paradigm known to be contingent upon magnocellular and parvocellular functioning.

Keywords: Flicker photometry; Brightness matching; Visual sub-system; Reading; Dyslexia

1. Introduction

Numerous psychophysical and physiological paradigms have been used during the past two decades to assess visual processing in specific reading disability (SRD) (Stein & Walsh, 1997). The application of parallel processing theories of vision to these findings has lead to the proposal that the majority of SRDs possess a visual processing disorder in transient system function, characterised as a loss of sensitivity for low spatial and high temporal frequency information (Lovegrove, Bowling, Slaghuis, Geeves, & Nelson, 1986). Support for the transient system deficit hypothesis (TSDH) has accrued from psychophysical paradigms such as contrast sensitivity (e.g., Lovegrove et al., 1982) visible persistence (e.g., Badcock & Lovegrove, 1981) and motion coherence (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995). The evidence also includes perceptual correlates of parallel processing, such as metacontrast masking and grouping paradigms (e.g., Solman, Cho, & Dain, 1991). Similar conclusions have been drawn from visual evoked potentials studies (most recently, Kubova, Kuba, Peregrin, & Novakova, 1996), fMRI of coherent motion (Eden et al., 1996) and anatomical findings that magnocellular neurones in the lateral geniculate nuclei of dyslexic brains are smaller than in non-dyslexic brains (Livingstone, Rosen, Drislane, & Galaburda, 1991) (dyslexia being one of the causes of reading disability). The evidence is, however, not without dissent in most of the techniques cited (Gross et al., 1995; Hogben, Rodino, Clark, & Pratt, 1995; Skottun, 2000; Spinelli et al., 1997; Vanni, Uusitalo, Kiesila, & Hari, 1997; Walther-Müller, 1995). The weight of evidence for a temporal processing deficit in SRD, implied by both auditory (Farmer & Klein, 1995) *and* visual dysfunction in SRD, should encourage researchers to expand the scope of experimentation.

The TSDH is based upon the existence of parallel processing visual sub-systems, for either colour or

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luminance contrast. These sub-systems, the magnocellular and the parvocellular, possess different spatial–temporal characteristics and the distinction was based upon layers within the primate lateral geniculate nucleus. Physiological evidence indicates that small parvocellular neurons are colour-opponent, have relatively low contrast sensitivity, high spatial and low temporal resolution, sustained responses and low conduction velocity. In contrast, large magnocellular neurons are broadband colour non-opponent, have high contrast sensitivity, low spatial resolution, high temporal resolution, transient responses and high conduction velocities. The psychophysically defined sustained and transient sub-systems show close correspondence with the spatio–temporal characteristics of the parvocellular and magnocellular sub-systems. The functional differentiation of the sub-systems has resulted in the suggestion that the M-cell/transient system is involved in the perception of motion and depth, the control of eye movements, the localisation of targets in space, and seems to perform a quick global analysis of the visual field. In contrast the P-cell/sustained system is involved in the identification of patterns, the resolution of fine detail, and the perception of colour (Williams & Lovegrove, 1992).

The processing of luminance and brightness, which has recently been related to the function of parallel visual sub-systems (Lennie, Pokorny, & Smith, 1993), has yet to be examined in SRD. Luminance, the photometric analog of radiance, is used to quantify the amount of visible energy of a source. The spectral nature of luminance is characterised by the relative luminance efficiency function (RLEF). The standard RLEF $V(\lambda)$ has its peak at 555 nm and is broadband in nature. Although defined as additive, using certain methods, the perception of spectral stimuli is non-additive. To illustrate, if spectrally very different colours are equated for luminance, we might expect the mixture, a different colour, to appear to be as bright as twice the reference white. In fact the mixture will be distinctly less bright than expected. This is indicative of an additivity failure. This failure is reflected in the well-known fact that different methods of heterochromatic photometry produce different RLEFs (refer Fig. 1) (Wagner & Boynton, 1972). Step-by-step and HBM functions are broader than those defined by heterochromatic flicker photometry and minimum distinct border (MDB) methods, which is attributed to failure of additivity (Wagner & Boynton, 1972).

Psychophysical and physiological evidence indicates that the $V(\lambda)$ function is determined by the achromatic channel, whereas brightness is processed by both the achromatic channel and the two opponent-colour channels. The contribution of chromatic channels to the perception of brightness accounts for the additivity failure of the equal brightness methods (Yaguchi, Kawada, Shioiri, & Miyake, 1993). The implication is that, using HFM, colour systems make no measurable contribution to the flicker match, while in HBM a contribution is evident (Lennie et al., 1993). Short wavelength sensitivity cones do not contribute to the non-opponent luminance system, as backgrounds which selectively alter S-cone sensitivity result in no change to flicker photometric sensitivity (Eisner & MacLeod, 1980).

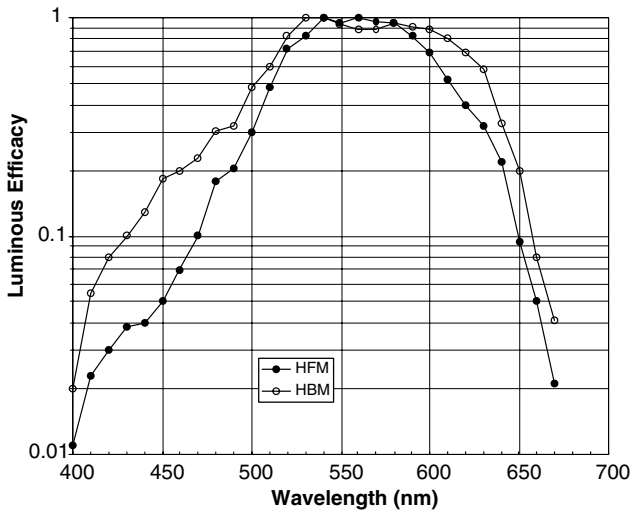

Fig. 1. Mean luminous efficiency functions using an equivalence criterion for minimum flicker and direct HBM redrawn from Wagner and Boynton (1972).

Psychophysical techniques used to examine parallel processing in SRD have focused upon temporal and spatial visual function especially contrast sensitivity and visible persistence. As luminance/brightness information may extend and clarify the understanding of parallel visual processing in SRD, the present study examined heterochromatic flicker matching and heterochromatic brightness matching (HBM) in samples of poor readers and age, grade and sex matched normal readers. It is hypothesised that the failure of colour additivity is greater in poor readers indicating a difference in visual processing compared with normal controls.

2. Methods

2.1. Subjects

Farmer and Klein (1995) and Hogben (1996) have noted the challenges that external validity presents in SRD research and have called for consistency in sample selection to address the issue. This study uses the Stanley and Hall (1973) criteria; a reading delay of 2.5 years or more, average or above average intellectual ability, English as a first language and absence of visual and auditory impairments and gross behavioural or emo-

tional problems. Consistent with recommendations of smaller delays for younger children (Stark, Giveen, & Terdiman, 1991) the reading criterion was modified. A 2.5 year delay in expected ability at 12 years was applied pro rata. The criteria were Year 3–12 months, Year 4–16 months, Year 5–20 months and Year 6–24 months. Therefore, this study assessed poor readers as opposed to SRDs. The definition of disability was contingent upon either reading accuracy or comprehension (Rutter & Yule, 1975). Intellectual ability was required to be no worse than 1 standard deviation below average (85) on the Raven's Standard Progressive Matrices (Raven, 1989).

In addition, the following acceptance criteria were used

1. Distance visual acuity—monocular 6/9 both eyes (aided if necessary) Landolt C acuity chart at 6 m.
2. Stereoacuity—better than 140 min of arc Titmus Fly Test of Stereopsis (Titmus Optical Company).
3. Oculomotor balance—No strabismus by cover test. $\leqslant 5^{\Delta}$ esophoria and $\leqslant 8^{\Delta}$ exophoria at 3 m and greater than $\leqslant 5^{\Delta}$ esophoria and $\leqslant 10^{\Delta}$ exophoria at 33 cm. $\leqslant 0.5^{\Delta}$ hyperphoria at either distance. Howell–Dwyer Phoria Card (Howell, 1991).
4. Colour Vision Deficiency—no more than 1 incorrect identification in the screening plates of the Ishihara Test of Colour Blindness (Ishihara, 1979).

Normal controls were selected using the same criteria with the exception they were to be reading at or above their chronological age for both accuracy and comprehension. Reading ability was assessed using the Neale Analysis of Reading (Neale, 1988).

Subject selection identified 30 poor readers and 30 age, grade and gender matched controls. As indicated in Table 1 (panel A) the poor readers and controls had mean IQs which were close enough as to not be an issue [$t(58) = 1.77$, $p = 0.08$] and ages that were essentially the same [$t(58) = 0.72$, $p = 0.48$]. Reading performance of the poor readers was significantly different from controls as a group [$F(1, 58) = 71.07$, $p < 0.05$]. There was a significant interaction of reading measure and group [$F(2, 116) = 4.25$, $p < 0.05$] with simple main effects analysis indicating the difference between controls and poor readers was more significant for accuracy and comprehension compared with rate. (Rate [$F(1, 58) = 16.36$, $p < 0.05$]; Accuracy [$F(1, 58) = 56.70$, $p < 0.05$]; Comprehension [$F(1, 58) = 88.57$, $p < 0.05$]). These subjects constituted the Neale 1 sample.

A post hoc evaluation of reading (18 month interval) resulted in exclusion of eight subjects and three controls. One subject declined participation for personal reasons during psychophysical testing. Discarded control subjects were replaced from an available pool. These subjects constituted the Neale 2 sample. As indicated in Table 1 (panel B) the poor readers ($N = 21$) and normal controls ($N = 21$) differed significantly in IQ [$t(40) = 2.70$, $p < 0.05$]. This was not considered important as both groups were well within the normal range. The groups were similar in age [$t(40) = 0.08$, $p = 0.94$]. Reading performance of the poor readers was significantly different to controls [$F(1, 40) = 60.50$, $p < 0.0001$] and the interaction of reading measure and subject was insignificant [$F(2, 80) = 0.39$, $p = 0.68$]. This result confirms the controls as a group were significantly better in all aspects of reading tested when compared with the poor readers.

Comparison of the Neale 1 and 2 data for the second sample revealed a high level of correlation for all reading measures (rate: [$r = 0.690$, $p < 0.05$], accuracy: [$r = 0.893$, $p < 0.05$], and comprehension: [$r = 0.823$, $p < 0.05$]). Further, when the difference in reading age between the tests (refer Table 2) of the second sample is analysed (ANOVA), a significant effect was found for group [$F(1, 40) = 8.61$, $p < 0.05$]. The main effect of reading measure [$F(2, 80) = 1.33$, $p = 0.27$] and the interaction of reading measure and group [$F(2, 80) = 1.52$, $p = 0.23$] were insignificant for this analysis. Therefore, across time the Neale 2 poor readers (as defined by the second reading assessment) continue to fit the reading lag criterion.

2.2. Apparatus and stimuli

Prior to experimentation, chromatic and luminance parameters were determined using a Minolta TV Colour Analyser calibrated by spectroradiometric methods of the Optics and Radiometry Laboratory (UNSW), which provide traceability, using spectral radiance and luminous intensity reference sources calibrated by the National Measurement Laboratory of Australia. Single phosphor and white average and range data were; red x mean 0.543, range 0.530–0.547, y mean 0.278, range 0.262–0.293, Y mean 18.09, range 12.95–23.39, green x mean 0.244, range 0.235–0.251, y mean 0.447, range 0.432–0.458, Y mean 61.13, range 46.65–90.23; blue x mean 0.152, range 0.145–0.155, y mean 0.066, range 0.055–0.072, Y mean 10.23, range 6.90–14.90; yellow x mean 0.413, range 0.399–0.439, y mean 0.496, range 0.484–0.508, Y mean 69.99, range 58.17–100.05. Stimuli were presented on Macintosh Colour Displays with 640 H×480 V pixel resolution. The monitors subtended a visual angle of 13.4 °H×10.1 °V when viewed from a distance of 100 cm. Both the HFM and HBM stimulus arrays consisted of a bipartite field of two rectangles, each 25 pixels in width (0.5° at 100 cm) and 50 pixels in height (1.05° at 100 cm). The chromatic components of the stimuli were chosen to approximate the unique hues and the specific inputs of the four, or two pairs of, colour processors in higher visual processing. The chromaticities used were determined with a method of

Table 1
The average age, IQ and reading scores (rate, accuracy and comprehension) for the poor readers and control children in Neale 1 (Panel A) and Neale 2 (Panel B)

	Controls ($N = 30$)	Poor readers ($N = 30$)	Statistic	p
Panel A				
Age				
Mean (SD)	9.24 (0.73)	9.11 (0.68)	0.72	ns
Range	8–10.75	8–10.25		
Raven's IQ				
Mean (SD)	102.57 (13.30)	96.77 (11.97)	1.77	ns
Range	87–140	85–140		
Reading rate				
Mean (SD)	10.01 (1.80)	8.24 (1.59)		
Range	6.08–13.08	6–11.09		
Reading accuracy				
Mean (SD)	10.87 (1.59)	8.06 (1.29)		
Range	8.42–13.8	6–11.2		
Reading comprehension				
Mean (SD)	10.31 (1.29)	7.53 (0.98)		
Range	8.33–12.92	6.25–10.83		
	Controls ($N = 21$)	Poor readers ($N = 21$)	Statistic	p
Panel B				
Age				
Mean (SD)	10.60 (0.62)	10.58 (0.68)	0.08	ns
Range	9.67–11.75	9.58–11.75		
Raven's IQ				
Mean (SD)	103.91 (14.37)	94.38 (7.82)	2.70	0.011
Range	89–140	85–106		
Reading rate				
Mean (SD)	11.02 (2.60)	8.34 (1.97)		
Range	7.33–17.33	6–12		
Reading accuracy				
Mean (SD)	12.12 (1.24)	9.15 (1.71)		
Range	9.42–13.5	6.42–13		
Reading comprehension				
Mean (SD)	11.31 (1.25)	8.21 (1.35)		
Range	9.17–13.8	6.17–11.4		

Standard deviations are shown in brackets.

Table 2
The average difference scores (rate, accuracy and comprehension) from the Neale 1 and Neale 2 reading assessments for poor readers and controls

	Controls	Poor readers
Reading rate	−1.45 (28.35)	−17.00 (13.31)
Reading accuracy	0.50 (11.28)	−5.77 (10.52)
Reading comprehension	−4.14 (14.63)	−8.45 (11.33)

Standard deviations are shown in brackets.

adjustment by two colour normal observers (RAF and SJD).

The HFM stimuli alternated a grey standard and a chromatic stimulus at 16.67 Hz counterphase flicker in a square-wave configuration. Luminance of the grey standard was set at 50% of the maximum luminance for each colour. The starting point for a staircase was 40% (RGY) and 30% (B) above and below the luminance of the reference grey. For each staircase the two chromatic stimuli were offset from the initial starting points at a disparity of 10% (R,G,Y) and 7.5% (B). The HBM task had the same rectangular dimensions and chromatic parameters used in the HFM task. The stimulus array consisted of a chromatic and a grey rectangle. Luminance of the grey standard was set at 50% of the maximum luminance for each colour. The two rectangles of the HBM stimulus array were separated by three pixels (0.06° at 100 cm) to inhibit the border as a visual cue to brightness. The ascending and descending staircases commenced with an offset 20% above and below the expected equiluminance points (R,G,Y) and 15% (B).

Step size was set at a constant 1% for HFM and, with the use of dithering, for HBM started at 15% and decreased by 50% per reversal until a minimum of 0.94%. The background for both tasks was set as 50% of grey (DAC values R = G = B = 127). The staircase rule used was one up one down.

2.3. Procedure

Both tasks used two-alternative forced-choice procedures in conjunction with double random interleaved staircases. The position of chromatic stimuli was randomised for both tasks. The HBM task required the subject to judge which of the two was brighter. For HFM the subject judged which of two rectangles possessed a more distinct sensation of flicker. For HBM the luminance level of the colour stimulus was varied until 10 reversals were produced. For HFM the offset, relative to the grey standard, of the two chromatic stimuli was varied. For both tasks the first six reversals were ignored and the final four used to calculate performance. Prior to testing subjects were provided with instructions, a demonstration and a practice session lasting approximately 8 min, which also served as an adaptation period. Responses were given using the right and left arrows of the computer's keyboard, corresponding to the right and left stimuli. Observers were seated 100 cm from the screen. No forehead or chin rest was used. Ambient luminance during experimental sessions was less than 1 cd m^{-2}.

3. Results

The RGB values were transformed using screen calibration data and RGB settings to luminance. Luminances were then converted to relative luminosity (RL) by dividing the luminance of the reference grey by the luminance value of the colour as matched. Analysis was conducted on the RL and a ratio of HBM to HFM relative luminosities. The latter method is consistent with Kaiser and Comerford (1975). This ratio provides a measure of relative parvocellular input to brightness sensation.

Repeated measures ANOVAs were performed on the RL data. For the Neale 1 data the main effects for task [$F(1,58) = 203.546$, $p < 0.05$] and colour [$F(3,58) = 53.524$, $p < 0.05$] were significant, with the interaction of task and colour significant [$F(3,174) = 43.215$, $p < 0.05$] (refer Fig. 2A). The main effect for group was insignificant [$F(1,58) = 2.348$, $p = 0.131$] and all other interaction effects involving group insignificant.

The ratio of HBM to HFM RLs varied significantly as a function of colour [$F(3,68) = 33.80$, $p < 0.05$]. A priori contrasts indicated that the red and blue stimuli exhibited significantly larger ratios when compared with the green and yellow [$F(1,236) = 52.10$, $p < 0.05$] (refer Fig. 2B). The main effect for group was insignificant [$F(1,58) = 2.34$, $p = 0.132$] and the interaction of group and colour was insignificant [$F(3,174) = 1.73$, $p = 0.162$].

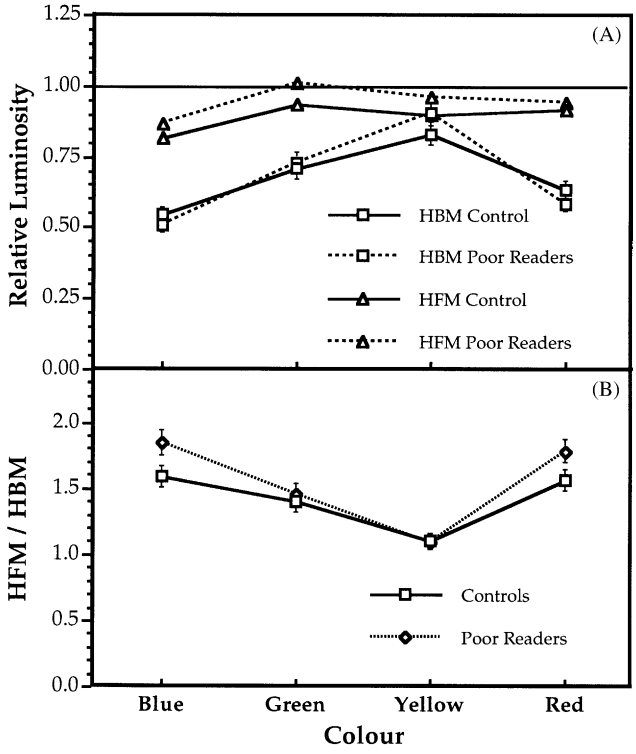

Fig. 2. HBM and HFM RLs (A) and HBM to HFM ratio (B) by colour for the Neale 1 sample. Error bars represent the standard error of the means.

The data analysis was repeated for the Neale 2 group. The RL main effects for task [$F(1,40) = 217.36$, $p < 0.05$] and colour [$F(3,120) = 37.24$, $p < 0.05$] were significant, and the interaction of task and colour was significant [$F(3,120) = 41.38$, $p < 0.05$]. The main effect for group was insignificant [$F(1,40) = 1.85$, $p = 0.182$], and the two-way interaction of task and subject [$F(1,40) = 6.70$, $p < 0.05$], the two-way interaction of colour and subject [$F(3,120) = 3.78$, $p < 0.05$], and the three-way interaction of task, colour and subject [$F(3,120) = 3.12$, $p < 0.05$] were all significant. Ratio data for the Neale 2 sample indicated a significant main effect for group [$F(1,40) = 4.40$, $p < 0.05$], a significant main effect for colour [$F(3,120) = 36.78$, $p < 0.05$] and a significant interaction of group and colour (Fig. 3) [$F(3,120) = 3.944$, $p < 0.05$]. Examination of the significant interaction using simple effects analysis (Howell, 1987) revealed significant differences between poor readers and controls for the red [$F(1,112) = 4.98$, $p < 0.05$] and the blue stimulus [$F(1,112) = 11.56$, $p < 0.05$]. These results require examination of simple effects for the HBM and HFM data. Significant differences were found between poor readers and controls for HBM red

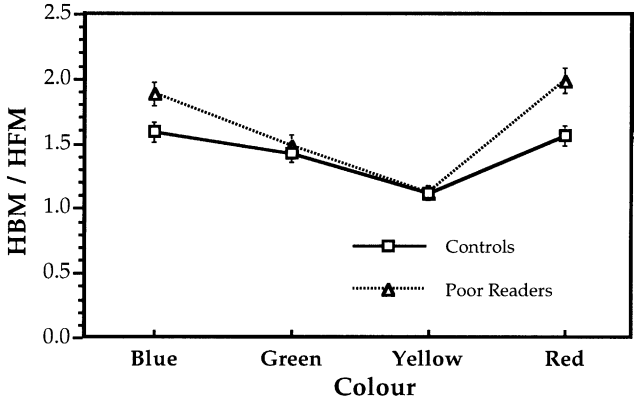

Fig. 3. HBM–HFM ratio by colour for poor readers and controls for the Neale 2 sample. Error bars represent the standard error of the means.

$[F(1,40) = 7.01, p < 0.05]$, HFM green $[F(1,40) = 7.25, p < 0.05]$ and HFM yellow $[F(1,40) = 8.92, p < 0.05]$ stimuli. All other simple effects were insignificant. The difference for the red and blue ratio data is supported by significant correlations between matches for red and blue stimuli for both the HBM and HFM and the ratio data (HBM Blue to HBM red $r = 0.58$, $p < 0.001$; HFM blue to HFM red $r = 0.34$, $p <= 0.05$; Ratio red to Ratio blue $r = 0.65$, $p < 0.001$).

4. Discussion

Relative luminosities for the HFM task were similar to the standard, indicating an additive process. From this data it is inferred that the HFM task was mediated by a process underlying the perception of luminance, which is assumed to reflect magnocellular system processing. Results for the HBM task showed significant colour specific additivity failure for the red and blue stimuli, while exhibiting additive results for the yellow stimulus. These outcomes replicate previous findings of significant additivity failure for spectral sensitivity using brightness matching techniques (Wagner & Boynton, 1972). These results are assumed to reflect the role of the colour coded systems in determining additivity failure for the brightness match for blue and red stimuli, and consequently the role of the parvocellular system in the perception of brightness.

Several significant main effects and interactions require consideration for the total sample. Firstly, the results for the HFM task are overall significantly different from the expected relative value of 1 for all colours. If the HFM task was solely contingent upon luminance information it was anticipated that a match of the standard and coloured fields would require the same level of luminance. This effect may arise from a number of sources. The photometer used to define stimulus luminances may differ from the CIE standard observer and young subjects will have relatively unyellowed crystalline lenses whereby Judd's modification of the CIE $V(\lambda)$ might be more appropriate.

The Neale 2 sample of readers (which excludes the subjects who were no longer classed as poor readers) reveals a significant main effect of colour. Poor readers produced significantly higher HBM/HFM ratios for both red and blue stimuli. There was no significant difference between the two groups for the green and yellow, although the values differ in a direction consistent with the red and blue results. Simple group effects analysis for the HBM and HFM tasks adds weight to the importance of the ratio of HBM to HFM relative luminosities which uses the subject as an internal control.

The differences for the red and blue ratio data is evidence for altered visual function in poor readers as defined within a parallel processing framework of vision. The significant interaction of colour and group for the HBM/HFM ratio, being a measure of parvocellular involvement, implies greater additivity failure in the perception of brightness/luminance information for red and blue stimuli in poor readers when compared with normal controls. This result may be interpreted a number of ways. It might indicate that poor readers have a dysfunctional parvocellular system which contributes directly to the red and blue non-additivity in RLEF as measured using HBM (Yaguchi et al., 1993). This interpretation is inconsistent with the TSDH as proposed by Lovegrove et al. (1986) which states that a large percentage of poor readers have transient system dysfunction. This hypothesis assumes normal sustained system function. It is, however, consistent with the suggestion of Wilkins (1995) who postulates a hyperexcitability in parvocellular functioning as a basis to reading disabilities. Alternatively it could be assumed that the parvocellular system in poor readers is normal (Lovegrove et al., 1986) and an insensitive or dysfunctional magnocellular system leads to a relative increase in parvocellular contribution to the perception of brightness. Both these hypotheses would attribute the anomaly to one of the two mechanisms contributing to the HBM match and, hence, to the sensation of brightness. An alternate explanation might be that the inputting mechanisms are normal, but that the interaction is in some way abnormal. This study does not provide the means to differentiate these interpretations but does provide clear evidence of a colour contingent difference between poor and normal readers for the perception of brightness.

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